Nuclear Physics on the Light Front

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High energy scattering experiments involving nuclei are typically analyzed in terms of light front variables. The desire to provide realistic, relativistic wave functions expressed in terms of these variables led me to try to use light front dynamics to compute nuclear wave functions. The progress is summarized here.

1. INTRODUCTION

Much of nuclear physics is concerned with the transition between nucleon-meson and quark-gluon degrees of freedom, with deep-inelastic lepton-nucleus scattering, Drell-Yan production and high energy (e,e'p) and (p,pp) reactions being some of the tools of investigation. Since high energies are involved, it is absolutely necessary to incorporate relativity. Our project is to implement Poincare invariance in nuclear physics by using light front dynamics. This is useful in analyzing experiments because the canonical momentum variable, k^+, is closely related to experimental observables. The challenge is to use these variables while incorporating the dynamical richness necessary to properly describe nuclei. Consider the plus-momentum distributions $f_{B,M}(k^+)$ which give the probability that a nuclear baryon B or meson M has a plus-momentum of k^+. If the relevant nuclear wave functions depend on k^+, the canonical spatial variable is $x^- = x^0 - x^3$. This leaves $x^+ = x^0 + x^3$ to be used as a time variable. Thus the light front dynamics is very different than the usual dynamics. If this light front formalism is used, $f_{B,M}$ are simply related to the square of the ground state nuclear wave function. Thus the use of light front dynamics provides vast simplicities, provided one can obtain the ground state wave function using realistic Lagrangians and many-body techniques. It is easier to carry out such a program for the effective hadronic Lagrangians of nuclear physics than for QCD because hadrons all have a non-zero mass and because the vacuum is not a condensed state of nucleon-anti-nucleon pairs. Another advantage is that the Fock state expansion of the wave function is in terms of on-shell particles.

The remainder is meant to present a brief outline of the progress. The main goal is to provide a series of examples to show that the light front can be used for high energy realistic-nuclear physics.

*This work is partially supported by the USDOE.

2. LIGHT FRONT QUANTIZATION OF HADRONIC LAGRANGIANS

You have to have a Lagrangian $\mathcal{L}$ no matter how bad. We use ones in which the degrees of freedom are nucleons, vector and scalar mesons and pions. The existence of $\mathcal{L}$ allows the derivation of the canonical-symmetric energy momentum tensor $T^{\mu\nu}$. In light front dynamics the momentum is $P^+ = P^0 + P^3$ where P^μ is the total momentum operator: $P^\mu = \frac{1}{2}\int d^2x_\perp dx^- \ T^{+\mu}$. The x^+ development operator is P^-. One necessary detail is that that T^{+-} must be expressed in terms of independent degrees of freedom. One uses the equations of motion to express the dependent degrees of freedom in terms of the independent ones, and uses these constraint equations in the expression for T^{+-}. Except for chiral Lagrangians, the necessary quantization procedure has been carried out long ago by other authors[1]-[3].

3. INFINITE NUCLEAR MATTER IN MEAN FIELD APPROXIMATION: PLUS-MOMENTUM DISTRIBUTIONS

The first problem we tried to solve is that of understanding nuclear matter in the mean field approximation using the Walecka model. This problem has been solved in a manifestly covariant manner[4], so that the existing results for the energy of the system provide a useful check of our light front procedure. We are able to reproduce the standard results [5,6].

The interesting feature of light front dynamics that one is able to calculate the plus-momentum distributions. For this simple problem we found that the nuclear vector mesons carry about a third of the nuclear plus momentum, but their momentum distribution has support only at $k^+ = 0$, with[7] $k^+ f_v(k^+) = 0.35 M_N \delta(k^+)$. Thus the vector mesons do not contribute to nuclear deep inelastic scattering. This zero mode effect occurs because in the mean field approximation, the meson fields of an infinite system are constant in both space and time.

This is an intriguing result which is caused by the large values of the scalar and vector potentials, which are characteristic of the Walecka model. The nucleons carry only 65% of the nuclear plus-momentum, a result in severe disagreement with deep inelastic scattering data. It is necessary to see if it survives for the case of finite-sized nuclei, and if correlations between nucleons are included.

4. FINITE NUCLEI IN MEAN FIELD APPROXIMATION

We showed[8,9] that the necessary variational principle is a constrained one which fixes the expectation value of the total momentum operator P^+ to be the same as that for P^-. This is the same as minimizing the sum of the total momentum operators: $P^- + P^+$. A new light-front version of the equation for the single nucleon modes was obtained, and a new numerical technique for their solution was introduced. The ground state wave function is treated as a meson-nucleon Fock state, and the meson fields are treated as expectation values of field operators in that ground state. The resulting equations for these expectation values was shown to be closely related to the usual meson field equations. The computed binding energies are essentially the same as for the usual equal-time theory. The nucleon plus momentum distribution $f_N(k^+)$ peaks for k^+ about seventy percent of the nucleon

mass, which again is far too small to be consistent with deep inelastic scattering data. The mesonic component of the ground state wave function was used to determine the scalar and vector meson momentum distribution functions, and the vector mesons were found to carry about thirty percent of the nuclear plus-momentum. We are currently investigating other Lagrangians which lead to smaller magnitudes of scalar and vector potentials and therefore yield better descriptions of the deep inelastic scattering data.

5. PIONS AND CHIRAL SYMMETRY

Light front quantization of a chiral Lagrangian can be performed [6], if one uses a Lagrangian due to Gürsey[10]. Pion-nucleon scattering at tree level was shown to reproduce soft pion theorems

6. NUCLEON-NUCLEON SCATTERING

The Weinberg-type equation[11] is the light front version of the Lippman-Schwinger equation. This equation is equivalent to the the Blankenbecler-Sugar equation, except that retardation effects need to be included[6]. Our hadronic chiral Lagrangian was used[12,13] to obtain a light front version of a one-boson-exchange nucleon-nucleon potential (OBEP). The accuracy of our description of the nucleon-nucleon (NN) data is good, and similar to that of other relativistic OBEP models.

7. NUCLEAR MATTER WITH NUCLEON-NUCLEON CORRELATIONS

The trivial nature of the vacuum in the light front formalism was exploited in deriving[12,13] the equations analogous to the the Hartree-Fock and Brueckner Hartree-Fock equations. Applying our light front OBEP, the nuclear matter saturation properties are reasonably well reproduced. The computed value of the compressibility, 180 MeV, is smaller than that of alternative relativistic approaches to nuclear matter in which the compressibility usually comes out too large. We showed that replacing the meson degrees of freedom by a NN interaction is a consistent approximation, and that the formalism allows one to calculate corrections to this approximation in a well-organized manner. The mesonic Fock space components of the nuclear wave function are studied also, and aspects of the meson and nucleon plus-momentum distribution functions are computed. We find that there are about 0.05 excess pions per nucleon.

The magnitudes of the scalar and vector potentials are far smaller than found in the mean field approximation. If we neglect the influence of two-particle-two-hole states to approximate $f(k^+)$ the nucleons are found to carry 81% (as opposed to the 65% of mean field theory) of the nuclear plus momentum. This represents a vast improvement in the description of nuclear deep inelastic scattering as the minimum value of the ratio F_{2A}/F_{2N} is increased by a factor of twenty towards the data, which is not enough to provide a satisfactory description. We can be optimistic about future results because including nucleons with momentum greater than k_F would substantially increase the computed ratio F_{2A}/F_{2N} since $F_{2N}(x)$ decreases very rapidly with increasing values of x and because M^* would increase at high momenta

Turn now to the experimental information about the nuclear pionic content. The Drell-

Yan experiment on nuclear targets [14] showed no enhancement of nuclear pions within an error of about 5%-10% for their heaviest target. Understanding this result is an important challenge to the understanding of nuclear dynamics [15]. Here we have a good description of nuclear dynamics, and our 5% enhancement is consistent[16], within errors, with the Drell-Yan data.

8. SUMMARY

The light front approach has now been applied to infinite nuclear matter in the mean field approximation, finite-sized nuclei in the same approximation, πN and NN scattering, and to correlated nucleons in infinite nuclear matter Thus it seems that one can use the light front approach to compute nuclear energies, wave functions and the experimentally important plus-momentum distributions. There are indications that the computed quantities will ultimately be in good agreement with experiment. But the use of light front dynamics in nuclear physics is only in its infancy, and much remains to be done to understand nuclear deep inelastic data the future expected flood of data on the (e,e'p) and (p,pp) reactions.

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